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Designing Ethical Cyber-Physical Industrial Systems

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Abstract: This paper deals with the risk of non-ethical behaviour of future cyber-physical industrial systems designed by researchers. The will of the authors is to foster researchers working on these innovative systems to pay attention to the possible consequences of their design on the welfare of humans interacting with these systems and their possible responsibility in case of an accident. Mainly focused on robotics, the literature relevant to ethics is shown to be scarce in the field of cyber-physical industrial system while relevant stakes are important. A set of recommendations is suggested and an example dealing with the industrial deployment of a cyber-physical system in transportation illustrates these recommendations.

Keywords: **cyber-physical systems, industrial systems, machine ethics, transportation.**

1. INTRODUCTION

Nowadays, there is an explosion of the number of autonomous physical systems, learning or not, that interact with humans and are connected through networks, typically in the domestic field (eg., lawn-mowers, drones, self-driving cars) but also in industries (eg., AGV, smart robots) as fostered by emerging concepts such as the German Industrie 4.0. This paper, co-written by a lawyer specialized in the domain of digital property and cyber-security and a researcher working in the field of industrial internet and **Cyber-Physical Industrial System** (CPIS), deals with the risk of non-ethical behaviour of future CPIS designed by researchers. The will of the authors is to foster researchers working on CPIS to pay attention to the possible consequences of their design on the welfare of humans interacting with these CPIS such as their possible responsibility in case of an accident. Futuristic non-scientific ideas more relevant to entertainment than science have initially put the light on this subject (as illustrated by the science fiction literature: Asimov's robotic laws, Mary Shelley's creature, Philip K. Dick short stories, etc.). Meanwhile, this subject became reality and went to the public place since the worldwide discussed recent case of the Tesla self-driving car crash that led to death (Ackerman, 2016). Since then, the whole research community has started to pay more attention to ethical and legal responsibility aspects of autonomous, intelligent and learning algorithms interfaced with physical moving elements, being robots, drones, domestic systems, etc. that interact with humans (denoted here ALS, standing for "**Automated Learning Systems**"). A CPIS is defined here as an industrial system composed of several of these kind of autonomous, heterogeneous, interacting and organized ALS (eg., robots, intelligent products, AGV), see (Lee et al., 2015) for a complete picture of this concept. This paper is focused on the case of CPIS since it is a clear application of the merging of the physical and digital worlds, inducing the potential introduced hazards. Focused on CPIS, discussions can easily be generalized to close engineering domains applying Cyber-Physical Systems (CPS) principles (transportation, urban, health-care engineering…) or to less close ones (finances, e-commerce, entertainment…) but obviously, not to the ones related to military systems or defence.

This paper is organized as follows. Section 2 points out the context and issues. Section 3 contains a short literature review. Section 4 presents some recommendations to researchers while section 5 illustrates in the domain of transportation, from authors' experience, the handling of suggested recommendations.

2. CONTEXT AND ISSUES

Ethics is initially a field of philosophy. According to (Morahan, 2015), ethical behaviour is concerned with actions that are in accord with cultural expectations relating to morality and fairness. Ethical aspects in engineering is not new and some journals are specialized in that field (Bird and Spier, 1995). These aspects have been studied in various fields of engineering, such as design (van Gorp, 2007) and obviously bio-engineering, including genetics (Kumar et al., 2016). In this paper, we address ethical issues from a

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designer (researcher) perspective in CPIS and we ask: *how to check or to ensure that a researcher's CPIS will behave ethically for the human society?* Rapidly, a second question emerges: *can a researcher be responsible if the CPIS he conceived in his lab, put on the market by an industrialist, provoked an accident?* We are thus rather concerned in this paper with of **machine ethics** (moral behaviour of artificial beings: *design of ethical CPIS*) than **techno/engineering ethics** (moral behaviour of human designing artificial beings: *ethical design of CPIS*).

The authors of this paper are not sure that researchers in CPIS have ever imagined that the answer to the second question could be "yes". Indeed, from our point of view, when an accident occurs, the difficulty to decide these aspects (e.g., who is legally responsible?) comes mainly from the fact that now several learning mechanisms and systems have reached industrial maturity and are embedded into autonomous physical systems interacting with others and with humans, far away from the research institutes where they came to birth.

To help to characterize more precisely this issue, we suggest to define and will discuss four levels of complexity for the designed autonomous physical system(s), see table 1.

Table 1. Potential ethical and legal responsibilities.

Complexity Level	*Characteristics of The level*	*Potential ethical and legal responsibilities (cumulative)*
Level 1	Single autonomous physical system Fully reliable, non learning	User, owner
Level 2	Single autonomous physical system Limited reliability, non learning	+ Maintainer, supplier, manufacturer, integrator
Level 3	Single autonomous physical system Limited reliability, learning	+ Autonomous physical system(s), Researchers/scientists/PhD students...
Level 4	Multiple autonomous physical systems in a CPIS, limited reliability, learning	

The *first* level of complexity (level 1) is basic and nearly unrealistic but it sets the initial situation: at this level, one considers an automated system (e.g., a robot) with a sufficient (nearly perfect) reliability level and no learning ability. In this paper, roughly speaking, a non-learning system is a system that will always generate the same deterministic outputs for the same deterministic inputs applied at different moments. If such an automated system harms a human, responsibilities can be determined using a procedural expertise under the habit that there should always be someone responsible for the harm. Since at this level the reliability is perfect, the one responsible is either an un-experimented user (misuse, etc.) or the owner. In that case, whatever happens, neither the automated system nor the manufacturer will never be judged the one responsible. There are nearly no ethical issue implying researchers at this level.

A *second* level of complexity, more realistic, concerns non perfect, non learning automated systems. At this level, one may consider a failure of a limited reliability automated system that causes a harm (due to a sensor or an actuator defect, etc.). The expertise of the responsibilities may now imply other types of actors in addition to the owner or the user (typically: part supplier, designer, integrator, manufacturer, maintainer, etc.), but still never the one of the automated system nor the one of researchers that designed it. It is important to note that some of these automated systems are nowadays designed to be in contact with humans (disabled people aid, remote surgery, exoskeletons, etc.), which increases the difficulties to expertise responsibilities when an injury results from a mutual interaction. Because of the limited reliability of these level 2 automated systems, some ethical issues start then to emerge but still not for researchers that designed these systems.

The *third* level of complexity is currently a hot topic, highly discussed even outside the research sphere. It concerns ALS assumed to have a limited reliability. Their learning capabilities are considered here in the sense described by (Mitchell, 1997): roughly speaking, a learning system is a system that may generate different but improved outputs for the same inputs at different moments. An ALS can cause harm because "classically" of internal breakdowns but also because of an unpredictable learned behaviour in normal use conditions, behaviour elaborated from unpredictable external solicitations: in that situation, can the supplier or the constructor of the system be fully responsible if he cannot control the solicitations of the ALS? Or can the scientist that initially designed the learning algorithms be sued for his algorithm handled and implemented in a ALS and put in the market by different successive stakeholders because this ALS harmed someone? To complicate the expertise, it is worth mentioning that the harm may be caused by an ALS whose learning knowledge exceeds the one of its designer in his working domain. At this level, one may thus consider that the responsibility may be the one of the ALS itself, for which it would be hard to traceable its decision process as it is done for humans. More, the consciousness of their limited reliability may render the ALS possibly aware of their own ongoing failure, implying some possible cornelian choices if one occurs (eg., one death vs. several major injuries). We find here the famous laws of Robotics from Asimov and their paradoxes that put the discussion a step ahead classical safety studies (Anderson, 2008).

Meanwhile, at this third level, a single ALS is considered. Thus, a *fourth* level of complexity emerges when one considers not a single but a set of various autonomous ALS with, for each, a limited reliability, such as the ones usually forming a CPIS for which emerging behaviours, that were not explicitly programmed, may be observed with time. The global learning of the CPIS, which is governed by mutual dynamic interactions and by interaction with the environment of its ALS, may cause harms. The machine ethics complexity comes from the fact that these ALS have been constructed from different providers, they may have different histories, have learnt from different sources of data and from interactions with different people. Ensuring that a researcher designs a CPIS that will behave ethically seems to be quite impossible, as the expertise for ethical responsibility in case of accident.

The question of ethical behaviour of designed systems is thus quite harder to decide when these systems are relevant to levels of complexity 3 and 4, the fourth one (the complexity level of CPIS) being much harder because of the uncontrollable interaction of several autonomous ALS. In the context of sustainable development and facing the rapid development of CPIS, researchers in automatic control must have to understand that they are now highly concerned by such ethical issues. The following part reviews the existing literature in the domain of ethics in the concerned fields and focuses more on machine ethics based on the previously introduced levels of complexity.

3. LITERATURE REVIEW

1.1 Techno/engineering ethics

From our review, techno/engineering ethics in industry have been addressed mainly in the fields of information and communication technologies (ICT) and robotic engineering. In ICT, the contributions concern more mostly cybersecurity, privacy, ethic usage of data, young people with the internet, etc. (Capurro, 2000), (Bhadauria et al., 2010), which is not directly related to our concern. Let us just mention the ETICA project which was a research project on "Ethical Issues of Emerging ICT Applications" funded by the European Commission under the 7th Framework Programme (GA 230318) during 2009-2011 (www.etica-project.eu/home).

The field of robotic engineering is more aligned with our concern. As an illustration, let us mention the works on autonomy-safety paradox of service robots (Matsuzaki and Lindemann, 2015), on ethical regulation of robotics in Europe (Nagenborg et al., 2007) and roboethics (Alsegier, 2016), (Lin et al., 2012). It is also worth mentioning the existence of a IEEE-RAS Technical Committee (TC) on Roboethics. Along with these contributions and groups, some projects have also been realized. In 2005, EURON funded the Project “Euron Roboethics Atelier”, with the aim of drawing the first Roboethics Roadmap. Let us also mention the EU Project Ethicbots (2005-2008) and the EU Project RoboLaw (Palmerini et al., 2016). In (Alsegier, 2016), two ethical theories are presented: rule utilitarianism theory and social contract theory.

From our review, we noticed that the main proposals fostering the adoption of techno ethics behaviours by researchers are often related to the idea of charters to be signed (“Hippocratic oath”).

1.2 Machines ethics

Machine ethics can be formally addressed at level 2 of complexity if all the different behaviours and states of the research object (the designed system) can be identified and verified or bounded (proofs). This is most of the time the case if in-depth studies are possible (model checking, proof by extension, etc.). In this context, a typical and historical approach is the systemic way of designing automated systems (top down design, functional analysis, safety studies, etc.) for which industrial R&D engineers are used to.

Machine ethics issues are amplified when autonomous systems are able to learn (levels 3 and 4). From our review, we noticed that researchers are often aware of machine ethics risks but they do not explicitly address it. The main approach met in the literature to limit these risks is to implement physical or informational “safety barriers”. Typical informational barriers are “low level”, and consist in bounding the functioning of an ALS to pre-given limits using static priority code lines (eg., “`if position_robot_x > threshold_x, then stop power`”). More elaborated barriers are still to be invented, especially if ALS and human must co-act, see (Marvel and Norcross, 2017) for a recent review on these technics.

At the level 3, a set of highly innovative works are being made, dealing with legal responsibilities of a learning entity from a lawyer’s point of view. It is obvious that there exists a huge corpus of “human being centered” laws, while quite none dealing with “artificial beings”. This implies what may be considered as the creation of a new specie aside the human one. This may also imply that human right constitutions should also be revised accordingly. For example, (Dreier and Döhmann, 2012) discussed the organization of administrative control and the legal liability regime which applies to service robots and the issue of autonomy of service robots.

Another example, which is from the authors’ point of view, among the most amazing studies, is currently led at the European Union (EU) Parliament level that worked on legal proposals related to robotics and artificial intelligence (AI)[1] (Delvaux, 2016). Apart from the recommendations’ main goals, which are human safety, privacy, integrity, dignity and autonomy, the EU Parliament aims to unify and incentivise European innovation in the area of robotics and AI. The means to achieve these goals would be specific legal rules concerning standardisation, intellectual property rights, data ownership, employment and liability. The ethical framework is composed of a Charter on Robotics (including a Code of Ethical Conduct for Robotics Engineers, a Code for Research Ethics Committees and Licenses for Designers and Users, based on EU Charter of Fundamental Rights’ principles) and relies on the creation of a European Agency for robotics and AI. Thus, these recommendations concern both aspects of ethics (techno and machine). We focus in the remaining on the machine ethics aspects.

According to these recommendations, a **smart autonomous robot** (SAR) is defined as follows:

- It acquires autonomy through sensors and/or by exchanging data with its environment (inter-connectivity) and trades and analyses data;

[1] European Parliament, 31.5.2016, Committee on Legal Affairs, Draft Report with recommendations to the Commission on Civil Law Rules on Robotics (2015/2103(INL))

- It is self-learning (optional criterion);
- It has a physical support;
- It adapts its behaviours and actions to its environment.

Different categories of SAR would be created. It is advised that a specific legal status for robots is created, so that at least the most sophisticated SAR could be established as having the status of **electronic persons**.

A SAR has rights and obligations (machine ethics). We summarize the main ones:

- Intellectual property and personal data: a SAR could create copyrightable work.
- Standardisation, safety and security: International harmonisation of technical standards is necessary according to the EU Parliament. The different areas where experiments with SAR are permitted should be identified.
- Individual rules: individual rules should be adopted for autonomous vehicles, care robots, medical robots, human repair and enhancement, as well as drones (remotely piloted aircraft systems, RPAS).
- Liability: a SAR should be held reliable for its actions according to the EU Parliament, which asserts that "*the greater a robot's learning capability or autonomy is, the lower other parties' responsibility should be, and the longer a robot's 'education' has lasted, the greater the responsibility of its 'teacher' should be*". Thus, the manufacturer, the programmer, the owner or the user should benefit from limited liability as SAR would be endowed with a compensation fund.

Therefore, a mandatory insurance system for robotics should be created on the basis of the actual car insurance system.

These works are clearly a step ahead the ones of the scientific community, but it is important to note that they are mainly done assuming the level 3 of complexity.

At level 4, only few works dealing with CPS are available. Among them, let us mention (Thekkilakattil and Dodig-Crnkovic, 2015) who proposed a framework for assessment and attribution of responsibility based on a classification of CPS with respect to the amount of autonomy and automation involved. Their proposal is based on the assumptions that different types of decision making occur inside a CPS: automatic, semi-automatic, semi-autonomous and autonomous decisions. Nearly no work has been identified in the emerging field of CPIS dealing explicitly with machine ethics at the fourth level (Trentesaux et al., 2016). It is clearly a lack since the inherent risks are induced by the intrinsic nature of a CPIS (merging physical and digital worlds), designed for autonomy, emergence of behaviour and close interaction with potentially harming physical elements. Obviously, dealing with the fourth level of complexity, it is hard for a researcher to state that its designed set of ALS inside his CPIS will behave ethically or not. The question is: *what researchers can do to control as much as possible the forthcoming risks of unethical behaviours of their designed CPIS?* For that purpose, a set of four elementary recommendations is provided.

4. SOME RECOMMENDATIONS TO RESEARCHERS

Recommendation #1: machine ethics are to be considered from the beginning of the research work and the definition of the needs, beyond classical safety studies. More precisely, it is important for a researcher to dissociate machine ethic-dependant decisions from machine ethic-*in*dependent ones during the whole design process of the CPIS. For each of the machine ethic-dependant ones, it is advised to realize a risk assessment and to implement redundant technological barriers to contain possible machine ethical risks. It is important to take time to imagine how the designed CPIS could be misused by error or rendered harmful (hijacked) using cyber-attack technologies for example. Time should be taken as well to imagine extreme conditions under which the stakeholders, including the researcher himself, could be sued and declared legally responsible of an un-ethical behaviour of the level 4 CPIS (trials) and then to adapt the implementation process to limit these risks. At least, a solution is to add a new decision criterion during the design process of the CPIS that is related to ethical issues during the functioning of the future CPIS, especially when choosing its functional specifications and when choosing the technological solutions to implement these desired functional specifications. Compensation of this criterion by other ones should not be possible (eg., by costs, reaction time, etc.). This implies for sure not only the assessment of the design choices according to such a complex criterion but also the accurate and axiomatic study of the relevant multi-criteria design decision process of the researcher. This process should gain from being explicitly identified, which is quite never done in fact.

Rec. #2: researchers should design the CPIS using a "human-centered" approach instead of a "techno-centered" one. That means that the future interaction of the different ALS composing the CPIS with the humans and especially, the end users, must be considered from the beginning of the design of the CPIS (including ergonomic and cooperation studies), and not at the end as researchers are often used to. Not doing this usually leads to the inefficient integration of the end user, considered then as a "magic solver", assumed to be able to solve all the problems the researchers did not address or even did not considered when they designed the CPIS. This will help to use the potential ability of humans when facing the unexpected while limiting involuntary and voluntary misuses of the CPIS (Trentesaux and Millot, 2016).

Rec. #3: it is advised to define a stepped design process, containing different validation stages. This is a classical design way, but what is suggested is to add "exaggerated tests" at each of the steps to test the robustness of the designed elements facing exaggerated risks, before the final targeted implementation of the CPIS. The first aim is to construct the CPIS on successive, robust, and standardized foundations, starting from the low-level atomic ALS to the full organization of the CPIS. The second aim is a crucial one: this process accompanies the evolution of the way of thinking of industrial engineers whose skills and knowledge, taught for years according to the introduced systemic, top-down, functional design method is somehow contradictory with the principles of a CPIS dealing with emergent behaviour, adaptation and self-learning mechanisms. Design support tools such as PDCA or SDCA can be useful in this aim. For sure, each of the previously validated step must be reviewed afterwards to search for errors not to be reproduced.

Rec. #4: all the stakeholders in charge of working on the future CPIS (eg., a project consortium) must search for a long term industry/research collaboration, steps ahead the current CPIS to develop, instead of a one shot project. This will limit the seek for short term ROI for all the stakeholders, including the researchers. The potential use of the CPIS in different applicative contexts beyond the one for which it has been thought must be envisaged. Working on its sustainability, according to the initial sense of the word (ie., long-lasting CPIS), can be seen as the ultimate assessment of its ethical behaviour or not: if a CPIS lasts and is naturally integrated in its environment, then it is useful and behaves ethically.

Our work is in its early stage but these recommendations can be seen as some necessary conditions, obviously nothing says that they are sufficient. Meanwhile, the authors think that their respect will ease the design of ethical CPIS by researchers. Based on these recommendations, the following part describes a case study and presents the way ethical aspects have been dealt with from the design until the exploitation of a kind of CPIS in the transportation industry sector.

5. AN ILLUSTRATIVE EXAMPLE IN TRANSPORTATION

The Surfer project, aiming to embed intelligent monitoring capabilities into train, was led by Bombardier Transport (Le Mortellec et al., 2013) and is an illustration of the proposed recommendations. Until recently, there was no real learning capabilities embedded in Bombardier trains. Thus, the diagnosis of designed systems, relevant to the introduced level 2 of complexity, was facilitated using for example a method that led to the specification, in an exhaustive way, of all the default codes and all possible states (cf. the principles of Safety Integrity Levels SIL). Consistent in the past generation of trains and naturally leading to the proof of ethical behaviour in train transportation as explained in the previous part, this approach becomes nowadays hardly feasible where the complexity of trains and the one of their control systems increase, as well as the expectations of train operators, with the risk of unforeseen states, events and situations because of a lack of time and financial support. To solve this, Bombardier has decided, through the Surfer project, to revise his diagnostic approach and to adopt an "intelligent monitoring" approach for it. The aim of the project was then to design the Surfer CPIS monitoring architecture that embeds decisional and cooperation entities into trains, associating each entity with a major critical system in terms of reliability and risks (eg., door access). The role of these ALS, modelled as holons, was to monitor locally the physical component in real time and, through cooperation and decision, trigger high level alarms for diagnostic.

What is new is that this evolution now leads Bombardier to address the fourth level of complexity since trains will be augmented with learning holons that are decisional entities interacting with each other, contributing to decisions about a system transporting humans. Since it is still not possible for scientists to prove the ethical behaviour of these holons, and to ensure that the project was to be a success, it has been decided several actions compliant with the previously introduced 4 recommendations. We present five of them.

Illustration of Rec. #1: the Surfer CPIS has been designed to not be merged with critical train systems. ALS were integrated as observers, the only interface with these critical systems being the plugins to the network to observe frames. There was no direct connection to monitored systems. Decisions from holons were designed to be only advise, never orders to be respected. Output signals of holons were never to potentially corrupt control/command signals. Input Signals were coming from observers/sensors with the minimal intrusion level if they were coming from safety dependant control networks of a train. The risk of provoking hazardous command, meaning an unethical behaviour, was then controlled.

Rec. #2: an acceptation factor from Bombardier's and train operators' engineers was the use of professional habits, and especially the use of the French GAMAB principles ("globally at least as good"). The use of such a principle ensures that successive versions of the Surfer CPIS will behave more and more ethically and ensure human acceptation.

Rec. #3: each line code to be embedded into holons into trains realized by the researchers has been rewritten, checked and compiled in an industrial-compliant way by the engineers of Bombardier. This limits the risk to write codes uncompliant with safety standards and ensures the capability of the engineers to appropriate and render the codes self-sustainable and self-maintainable by Bombardier, limiting the risk to face short-term hazardous or unethical behaviors of holons.

Rec. #3: an iterative process, with strong intermediary validation steps has been defined at these different stages which were: 1) definition of the global holonic architecture; 2) design of the core algorithms for each holon; 3) lab prototyping of the architecture; 4) lab validation of the architecture using an advanced emulation of a real train control network facing exaggerated risks and events. This has been done for each improvement of the core algorithms (test of embedability and memory use; test on real data; etc.). This process ensures that the research activities were well aligned with train operator's specifications, limiting the risk to face long-term hazardous/unethical behaviors of holons.

Rec. # 4: to ensure a long-term sustainable view, Bombardier Transport, Prosyst (SME) and the University of Valenciennes (UVHC) have constructed a joint research lab., called SurferLab dealing with Distributed Intelligence for Transportation Systems[2]. This joint research lab enables the continuous improvement of the Surfer CPIS with attention paid to its long-term societal and environmental impacts.

Thanks to such an approach, the Surfer CPIS corresponds to a real need, it is not intrusive in state-of-the-art industrial methods, it does not generate new risks for human safety and months after the implementation of some of its parts in several trains, the CPIS is still in use. All these elements tend to state that this CPIS presents a sufficient level of ethical behaviour (else, the CPIS would have been rapidly rejected by the stakeholders).

CONCLUSION

In this paper, a set of necessary but not sufficient recommendations have been suggested for researchers to ensure that their designed CPIS behave ethically. It is noticeable that the legislators are ahead of the researchers about ethical and legal responsibility of ALS (level 3) but there still remains a lot to do to reach the level 4 of complexity, which is the level relevant to CPIS. Obviously, we are at the beginning of works on ethical CPIS, but our first (rather limited) experience provides some interesting insights about next steps to proceed. We identified for example the urgent need to quantify and to measure the ethical performance of a CPIS. The authors encourage researchers to debate about and work on ethical aspects in cyber-physical industrial systems (and relevant concepts: Industrie 4.0, smart manufacturing, industrial internet, etc.).

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